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The environmental and economic impact of removing growth-enhancing technologies from U.S. beef production[1]

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ABSTRACT: The objective of this study was to quantify the environmental and economic impact of withdrawing growth-enhancing technologies (GET) from the U.S. beef production system. A deterministic model based on the metabolism and nutrient requirements of the beef population was used to quantify resource inputs and waste outputs per 454×10^6 kg of beef. Two production systems were compared: one using GET (steroid implants, in-feed ionophores, in-feed hormones, and beta-adrenergic agonists) where approved by FDA at current adoption rates and the other without GET use. Both systems were modeled using characteristic management practices, population dynamics, and production data from U.S. beef systems. The economic impact and global trade and carbon implications of GET withdrawal were calculated based on feed savings. Withdrawing GET from U.S. beef production reduced productivity (growth rate and slaughter weight) and increased the population size required to produce 454×10^6 kg beef by 385×10^3 animals. Feedstuff and land use were increased by $2,830 \times 10^3$ t and 265×10^3 ha, respectively, by GET withdrawal, with $20,139 \times 10^6$ more liters of water being required to maintain beef production. Manure output increased by $1,799 \times 10^3$ t as a result of GET withdrawal, with an increase in carbon emissions of 714,515 t/454×10^6 kg beef. The projected increased costs of U.S. beef produced without GET resulted in the effective implementation of an 8.2% tax on beef production, leading to reduced global trade and competitiveness. To compensate for the increase in U.S. beef prices and maintain beef supply, it would be necessary to increase beef production in other global regions, with a projected increase in carbon emissions from deforestation, particularly in Brazil. Withdrawing GET from U.S. beef production would reduce both the economic and environmental sustainability of the industry.

Key words: beef, carbon footprint, economic sustainability, environmental sustainability, growth-enhancing technologies, productivity

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INTRODUCTION

The U.S. livestock industry faces a considerable challenge in producing sufficient animal protein to fulfill the needs of the growing national population. The global population is predicted to increase from the current 7 billion people to >9.5 billion by the year 2050, with the Food and Agriculture Organization (**FAO**; 2009) projecting a 70% increase in demand for meat, milk, and eggs. Therefore, the livestock industry must produce more food using fewer inputs as competition for land, water, and energy intensifies.

Improving productivity (growth rate and slaughter weight) within the U.S. beef industry between 1977 and 2007 reduced resource input and waste output per kilogram of beef (Capper, 2011). To maintain the social license to operate in a demand-driven market, where the environmental impact of livestock production is a significant concern, it is essential to further improve productivity and demonstrate the commitment of the industry to sustainability. A positive relationship exists between improved productivity and both environmental and economic sustainability; whereby, as resource use is reduced per unit of animal protein, economic return also increases.

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Consumers are concerned about the environmental impact of food products (Wandel and Bugge, 1997) and the use of growth-enhancing technologies (**GET**) in animal production; however, the positive relationship between improved productivity and environmental benefits is not widely understood outside the livestock industry. Processors and retailers often use consumer concerns as a rationale for constraining GET use; yet, Lusk et al. (2003) demonstrated no difference in consumer valuation of beef from hormone-treated or nontreated animals in the United States, Germany, and United Kingdom. To date, no data are available on the combined environmental and economic effects of GET use on the sustainability of the beef industry. This paper will analyze environmental and economic impacts of withdrawing GET from the U.S. beef industry.

MATERIALS AND METHODS

This study used data from existing literature and databases, and required no Animal Care and Use Committee approval.

A deterministic model based on the nutrient requirements and metabolism of animals within all sectors of the beef production system as described by Capper (2012) was used to quantify the environmental impact of 2 U.S. beef production systems. Management practices within the two production systems were identical, except for the use of GET (where permitted, according to label use approved by the U.S. Food and Drug Administration) in the "conventional" (**CON**) system, with no GET being used in the "no technology" (**NOT**) system. Environmental impact was calculated by comparing resource inputs and waste output of each beef production system, expressed per 454×10^6 kg of beef (HCW) produced in 365 d.

The Beef Production System Environmental Model

Detailed data relating to the environmental model system is described in Capper (2011, 2012). To briefly summarize, the model incorporated all relevant resource inputs and waste outputs into a deterministic model based on animal nutrition and metabolism. System boundaries extended from the manufacture of cropping inputs (fertilizers, pesticides, herbicides) to arrival of animals at the slaughterhouse. The model included three animal subsystems. The cow-calf unit contained animals that served to support population dynamics (cows, calves, replacement heifers, adolescent bulls, yearling bulls, and mature bulls). The stocker/backgrounder operation contained weaned steers and heifers fed until they reached sufficient weight to be placed into the feedlot. The feedlot contained both calf-fed (beef and dairy animals that enter the feedlot at weaning) and yearling-fed (beef animals that enter the feedlot after the stocker stage) animals that were fed until the desired BW and finish were achieved. Animal rations were formulated based on characteristically used feedstuffs to supply sufficient nutrients to support maintenance and production (pregnancy, lactation, and growth, where appropriate); thus, feed and cropping resources were derived from formulated rations. Primary resource inputs into the animal subsystems included animal feed and drinking water, unit electricity, and fuel for animal transport between subsystems and feed transport to farm. Secondary inputs included chemicals (fertilizer, pesticides) applied to feed crops, irrigation water, and fuel for both cropping practices and agrochemical manufacture. All data inputs to the model are described by Capper (2012), except for the modifications detailed below.

Beef Production System Characteristics

Both beef production systems included cow-calf, stocker, and feedlot operations, modeled according to characteristic U.S. production practices (USDA, 2000a,b, 2009a,b), with population characteristics unaffected by GET use as detailed in Capper (2012). Briefly, these included a 365-d calving interval, 207-d lactation, and calving rate of 91.5%, with 96.5% of calving cows producing a live calf. Replacement heifers were included in the population at a rate of 0.27 heifers/cow, with an annual replacement rate of 12.9% and a 24-mo age at first calving. Bulls were included in the population at a ratio of 1 bull:25 cows. Mortality rates were assigned based on subsystem-specific values from USDA (2000a, 2009a). The U.S. beef industry includes animal inputs from the U.S. dairy industry in terms of cull cows, plus male and female calves at 3 d of age. Resource inputs and waste output between the dairy and beef systems were calculated based on a biological allocation method. A deterministic model of resource use and environmental impact within dairy production was previously developed by Capper et al. (2009), based on the same nutrition and metabolism principles as the current beef model. Using the model described by Capper et al. (2009) ensured that resource input data for both models were sourced from similar data, thus minimizing conflict between models. The dairy model was used to determine the proportion of total resource inputs and waste output attributable to growth in Holstein heifers from birth up to 544 kg BW at which they would be sold as beef animals if they did not enter the dairy herd. These totals represented the environmental cost attributed to dairy cull cows entering the beef market and were applied to the appropriate beef production, according to the number of cull cows within each system. The impact of producing male and female dairy calves for calf-fed rearing was calculated by partitioning out the proportion

Table 1. Mean production data[1] for subclasses of growing and finishing animals

Item	System[2]	Time spent in subclass, d	ADG, kg/d	DMI[3]	G:F[4]	Initial BW, kg	End BW, kg	Slaughter data	
								Age, d	Weight, kg
Preweaned beef calf	CON	207	1.02	N/A	N/A	33	244	N/A	N/A
	NOT	207	1.02	N/A	N/A	33	244	N/A	N/A
Preweaned dairy calf	CON	56	0.89	N/A	N/A	40	92	N/A	N/A
	NOT	56	0.89	N/A	N/A	40	92	N/A	N/A
Stocker	CON	148	0.82	15.1	0.119	246	367	N/A	N/A
	NOT	159	0.76	15.0	0.112	247	367	N/A	N/A
Yearling-fed[5] beef breed	CON	116	1.71	22.0	0.169	374	573	482	573
	NOT	116	1.32	19.5	0.149	366	526	487	526
Calf-fed[5] beef breed	CON	209	1.50	18.1	0.181	257	569	416	569
	NOT	209	1.18	15.9	0.163	249	502	421	502
Calf-fed dairy breed	CON	277	1.74	17.6	0.234	112	594	333	594
	NOT	277	1.44	15.1	0.211	104	510	338	510

[1]Modeled based on animal characteristics, growth rates and desired slaughter weights according to AMTS CattlePro (2006).
[2]CON = conventional; NOT = no technology; further details of the systems are given in the materials and methods section.
[3]Reported DMI for each stage is the mean DMI for the classes of animals within that stage weighted for animal numbers.
[4]Reported F:G for each stage is the mean DMI for the classes of animals within that stage weighted for animal numbers.
[5]Yearling-fed animals enter the feedlot after a stocker stage; calf-fed animals enter the feedlot after weaning.

of total resource inputs and waste output attributable to pregnancy in lactating and dry dairy cows. This cost was adjusted for the number of dairy calves in the beef system and thus the number of cows required, before application to the beef production system.

Nutrient requirements of each class of animals (lactating cows, dry cows, replacement heifers, bulls, adolescent bulls, preweaned calves, stocker animals, calf-fed feedlot-finished animals, yearling-fed feedlot-finished animals, and dairy feedlot-finished animals) were calculated using AMTS (2006) Cattle Pro, a commercial cattle diet formulation software package based on the Cornell Net Carbohydrate and Protein System. Animal diets were formulated to fulfill the requirements of animals within each class and subsystem, according to age, sex, breed, BW, production level, and GET use.

A total of 46 different diets were formulated to supply the various groups of animals with their dietary requirements as predicted by AMTS Cattle Pro (2006). Diets for animals in the supporting population (lactating and dry cows, replacement heifers, mature and adolescent bulls) were formulated based on pasture, grass hay, and straw diet, adjusted for a predominantly pasture-based diet during spring and summer, with conserved forage supplementation as required during fall and winter. Grazed pasture use was based on intakes predicted by AMTS Cattle Pro (2006), according to cattle BW, sex, and production level. No differences in grazed pasture quality were assumed between treatments; nutritive values for pasture were derived from default values within AMTS Cattle Pro (2006), with pasture yields according to Brink et al. (2008). Before weaning at 207 d (USDA, 2009a), beef calves suckled from the dam and consumed pasture and starter feed (flaked corn and soybean meal) at intakes calculated according to AMTS Cattle Pro (2006). Post-weaning, 83.5% of beef calves (Capper, 2011) entered the stocker subsystem where they were fed diets containing pasture, grass hay, corn silage, flaked corn, and soybean meal, according to seasonal pasture availability that assumed average-quality pasture was available for 8 mo of the year. At 12 mo of age, stocker cattle entered the feedlot as yearling-fed finishing animals. Diets for yearling-fed feedlot steers (42% of population) and heifers (58% of population) were balanced for predicted DMI and growth rates (Table 1), and included corn grain, soybean meal, alfalfa hay, and vitamin/mineral supplements. Approximately 16.5% (Capper, 2011) of weaned beef calves entered the feedlot directly as calf-fed finishing animals and were fed a diet formulated from similar ingredients as the ration of yearling-fed animals, formulated for predicted DMI and average growth rates as documented in Table 1.

A total of 12.9% of total feedlot animals originated from dairy production, including 11.5% dairy steers and 1.4% dairy heifers (USDA, 2000a; Capper, 2011). Within the model, dairy calves were fed milk replacer (with environmental impact accounted for as a function of milk production and processing) and a calf starter ration (flaked corn and soybean meal) until weaning at 56 d. Dairy calves entered the feedlot on a calf-fed basis and were finished on a standard feedlot diet, similar to that fed to the calf-fed beef animals, which was balanced for predicted DMI and growth rate (Table 1).

The CON system included the use of GET, steroid implants, in-feed ionophores (monensin sodium, lasalocid sodium), in-feed hormones (melengestrol acetate, **MGA**), and beta-adrenergic agonists (ractopamine hydrochloride,

Table 2. Characteristics of growth-enhancing technologies used within the model

Item	Chemical Class	Productivity effect	Supplemented animals[1]	Adoption rate[2]
Ionophores	Ionophores	Improved feed efficiency and rate of BW gain	Stocker steers/heifers Finishing steers/heifers	19%[3] 90%[4]
Melengestrol acetate (MGA)	Synthetic progestins	Increased rate of BW gain, improved feed efficiency, estrous suppression[2]	Finishing heifers	90%[4]
Steroid implants	Estrogenic and androgenic steroids	Increased rate of BW gain, improved feed efficiency	Calf-fed steers/heifers Stocker steers/heifers Yearling-fed steers/heifers	85.7%[5] 6.8%[5] 89.2%[5]
Beta-adrenergic agonists	Beta-adrenergic agonists	Increased carcass leanness, dressing percentage, improved rate of BW gain and feed efficiency	Finishing steers/heifers	38%[4,6]

[1]Further details are given in the Materials and Methods section.

[2]Percentage of animals supplemented.

[3]Elanco Animal Health, Greenfield, IN.

[4]Pfizer Animal Health, Terre Haute, IN.

[5]USDA (2000a).

[6]Intervet Schering-Plough Animal Health, De Soto, KS.

zilpaterol hydrochloride, **βAA**), with biological effects and current industry adoption rates as detailed in Table 2. The assumption was made that beef producers were more likely to build technology use in a step-wise manner (i.e., were more likely to use βAA if they were also using steroid implants and ionophores); thus, each class of animals included several subclasses (e.g., ionophore only, ionophore + implant, ionophore + implant + βAA) with varying performance characteristics (Table 2). The authors note that the ionophore monensin sodium is approved for use in cows within the cow-calf system; however, the lack of solid adoption rate data meant that this GET was not included within the analysis for this subsystem.

The AMTS Cattle Pro (2006) software corrects feed intake, efficiency, and growth rate for the use of steroid implants, ionophores, or their combination in growing and finishing animals. Therefore, this was used when formulating diets for growing (stocker and feedlot) animals supplemented with these technologies. Due to lack of data for the effects of implant use in preweaned calves and low national adoption rate within these animals (USDA, 2000a), this GET was not included in the preweaned calf groups. The effects of MGA use in heifers were modeled according to data from Perrett et al. (2008) and Sides et al. (Elam et al., 2009; Montgomery et al., 2009a; Montgomery et al., 2009b; Scramlin et al., 2010; Sides et al., 2009), which showed a mean central tendency toward a 3.5% increase in feed intake compared with nonsupplemented animals. Research relating to the productivity effects of βAA demonstrated a mean central tendency to increase growth rate by 18.4% during the supplementation period (28 d for ractopamine hydrochloride, 20 d for zilpaterol hydrochloride) across all classes of supplemented animals (Schroeder et al., 2004; Anderson et al., 2005; Laudert et al., 2005a,b; Abney et al., 2007; Elam et al., 2009; Montgomery et al., 2009a,b; Vogel et al., 2009; Scramlin et al., 2010;). The dressing percentage for animals supplemented with βAA averaged 63.8% compared with 63.3% for nonsupplemented animals (Schroeder et al., 2004; Anderson et al., 2005; Laudert et al., 2005b; Elam et al., 2009; Montgomery et al., 2009a,b; Vogel et al., 2009; Baxa et al., 2010; Scramlin et al., 2010;).

Slaughter population for both systems included calf-fed and yearling-fed beef steers and heifers, calf-fed dairy animals (steers and heifers), and cull animals from the beef and dairy sectors (cows and bulls). Subclasses of feedlot-finished animals were taken to the same number of days on feed within both model; for example, 116 d on feed for yearling-fed beef steers in both the CON and NOT systems, as shown in Table 2. The average slaughter weight across all animal categories was 574 kg in the CON system and 521 kg in the NOT system.

Manure production and N and P excretion for animals within each subsystem were calculated according to the animal and diet-specific output values from AMTS Cattle Pro (2006). Dietary-soluble residue, hemicellulose, and cellulose intakes were used to calculate enteric CH_4 production from all animals within each subsystem, including preweaned calves (Moe and Tyrrell, 1979). The fraction of N emitted as enteric N_2O was modeled using data reported by Kaspar and Tiedje (Kaspar and Tiedje, 1981), and Kirchgessner et al. (1991). Emissions of CH_4 from manure were estimated using methodology prescribed by USEPA (USEPA, 2010), based on the quantity of volatile solids excreted, maximum CH_4-producing potential (0.24 m^3/kg of volatile solids), and a conversion factor specific to either pasture or feedlot systems. Intergovernmental Panel on Climate Change (IPCC, 2006) emission factors were used to calculate N_2O emissions from manure. Biogenic carbon, which rotates continuously through a cycle including uptake of atmospheric carbon by crops followed by a return to the atmosphere through animal respiration, was considered to be neutral with respect to GHG emissions. Carbon sequestration into soil and CO_2 produced through animal respiration were considered to be equivalent and were therefore not specifically accounted for.

Water use, electricity use, and cropping practices are detailed in the model described by Capper (2012). Environmental impact of feed ingredients was accounted for in terms of cropping input manufacture and agronomical practices (including harvest). Animal and feed transport within the CON and NOT systems are similarly detailed by Capper (2012), with animals being transported an average of 483 km between subsystems and 161 km to the slaughterhouse, and feed (corn and soy) being transported 558 km to the feedlot.

Withdrawing GET from the U.S. beef production system would have an effect equivalent to imposing a tax on beef production. Results from the environmental model were used to calculate the economic impact of this "tax" on U.S. beef production by placing a value on the additional feed inputs required to maintain beef production without GET use. It is noted that in the current beef industry, natural cattle are a niche market and thus gain an economic premium compared with conventional cattle; however, within the current study, withdrawal of GET would result in all cattle being "natural." Thus, the current price premium would cease to exist. National market prices (including a return to the land, labor, and management skills required to produce these commodities) averaged across all states and months of 2009 from the National Agricultural Statistics Service (USDA, 2009c) for all inputs, except corn silage and pasture, were used to quantify the economic value of the extra feed inputs required. Monetary values placed on corn silage and pasture were based on data from the University of Minnesota (USDA, 2009d) and personal communication with extension specialists (M. Duffy and W. Edwards, both in the Economics Dept. at Iowa State University), who suggested that the economic value of pasture is one-fourth of the value of hay (http://www.extension.iastate.edu/agdm/wholefarm/html/c2-23.html). Economic values for GET were provided by personal communication with M. Ackerman (Lextron Animal Health, Greeley, CO) and J. Young (Micro Beef Technologies, Amarillo, TX).

RESULTS AND DISCUSSION

The environmental sustainability of beef production is a significant concern for all stakeholders within the food production system. On a global basis, livestock are claimed to account for 18% of greenhouse gas emissions (Food and Agriculture Organization of the United Nations, 2006) and USEPA (2010) calculates that beef production contributes 2.1% of total U.S. greenhouse gas emissions (**GHG**). Previous studies within the U.S. beef and dairy industries (Capper et al., 2008, 2009; Capper, 2011, 2012) indicate that improving productivity has a positive mitigating effect on resource use and waste outputs from livestock production.

The current study demonstrates improvements in productivity within the CON system compared with the NOT system. As originally described by Bauman et al. (1985) in dairy cattle and applied to beef cattle by Capper (2011), improved productivity (milk yield in dairy cattle, growth rate in beef animals) facilitates the "dilution of maintenance" effect. The dilution of maintenance effect works within the beef production system both at the individual animal and population levels. As the growth rate per animal increases, the proportion of the total daily nutrient requirement used to maintain the vital functions of the animal (i.e., the "fixed cost" of beef production) is reduced. In this instance, nutrient requirements can be used as a proxy for resource use and waste output, as nutrient requirements are directly linked to feed, water, land, fossil fuels, manure production, and GHG emissions. Improved growth rates seen within the CON system in the current study (Table 1), therefore, confer the dilution of maintenance effect, reducing the resources required to produce an equivalent quantity of beef when compared with the NOT system.

A reduction in slaughter weight (Table 1) and dressing percentage of finished beef animals further increases the resources required for beef production as a greater number of slaughter animals is required to produce a set quantity of beef. The total slaughter population consists of both beef and dairy animals, with the number of dairy animals entering the beef production chain being primarily governed by 3 factors: dairy population size, culling rate, and quantity of male dairy animals produced. Assuming a static dairy population size, an increase in the number of animals required to fulfill meat demand, therefore, necessitates an increase in the size of the supporting beef population that exists to provide beef calves. Within the current study, animals were finished after a constant number of days on feed; thus, GET withdrawal resulted in a reduction in average slaughter weight of 53 kg (521 kg in NOT animals, 574 kg for CON animals; Table 1). In combination with the decrease in dressing percentage conferred by the removal of βAA, the NOT system, therefore, required a total of 3,651 $\times 10^3$ animals in the beef population (slaughter animals plus supporting population) to produce 454 $\times 10^6$ kg beef, compared with 3,266 $\times 10^3$ animals in the CON system, an increase of 11.8% (Table 3). The principal product of the beef industry is meat; animals within the supporting population ultimately contribute to beef production after several years but are maintained up until that point to produce offspring to be reared for slaughter. The total feed energy cost of the supporting population may, therefore, be considered as an additional "fixed cost" of beef production. The 8.3% increase in the population feed energy (8,515 $\times 10^6$ MJ ME) required to produce 454 $\times 10^6$ kg of beef in the NOT system, therefore, provides an example of an inversion of the dilution of maintenance effect at the population level.

Total feedstuff use in the NOT population was 29,637 $\times 10^3$ t, a 10.6% increase compared with the CON population (Table 3). Despite the lack of GET within the NOT system, no difference in the use of GMO or other cropping technologies existed between the feed production practices that supplied either system; thus, feed and land use differences are directly related to changes in animal productivity. Land use is predicted to be a major factor affecting the future sustainability of animal production, particularly as the population increases and competition intensifies among recreational, housing, industrial, and agricultural land uses (Smith et al., 2010). Withdrawal of GET from the beef production system increased the quantity of land required to produce 454 × 10^6 kg of beef by 10.0% (2,909 × 10^3 ha in the NOT system vs. 2,644 × 10^3 ha in the CON system). Given that the U.S. beef industry produced 11.8 billion kg of beef in 2010, this would amount to a predicted total land use of 75,763 × 10^3 ha for beef production (an extra 2,886 × 10^3 ha compared with CON production) if GET were withdrawn from U.S beef production. To put this number into context, 75,763 × 10^3 ha is greater than the entire land area of Texas. The U.S. beef industry currently acts as an excellent translation agent for poor-quality forage indigestible by humans to be converted to high-quality animal protein via the cow-calf operation. Nonetheless, an increase in land use of this magnitude would require land that is currently being used for other agricultural or recreational purposes to be converted to pasture, corn, and soybeans, adding weight to the argument that livestock compete with humans for food resources.

Potentially, the most serious consequence of the increasing global population and consequent requirement for food production is the increase in the number of regions where freshwater has become scarce. According to FAO of the United Nations (2006), >1.7 billion people live in water-scarce areas (<1,000 m^3 annual precipitation per person), with a further 2.3 billion people inhabiting water-stressed basins (1,000 to 1,700 m^3 annual precipitation per person) and >1 billion people who do not have access to sufficient clean water. The underlying reasons for water scarcity are myriad, yet, the underlying cause is an increase in water withdrawals (regardless of end use) and poor water management. The increase in irrigation for crop production and potable water for livestock production and processing are often implicated as major contributors to water use for animal production (Beckett and Oltjen, 1993; Peters et al., 2010); thus, the adoption of management practices that reduce water use per unit of animal protein would be expected to improve the sustainability of beef production. The increased population size conferred by withdrawing GET from the beef production system in the current study increases the requirements for both animal drinking water and cropland irrigation, yet, the magnitude of the difference was less than other resources at 4.2% (499,297 × 10^6 L in the NOT system, 479,159 × 10^6 L in the CON system; Table 3).

Table 3. Resource inputs, waste output, and environmental impact associated with producing 454 × 10^6 kg of beef from a conventional (CON) U.S. production system compared with a production system without growth-enhancing technology use (NOT)

System	CON	NOT	Δ[1]
Animals			
Supporting population,[2] × 10^3	2,503	2,763	261
Stockers, × 10^3	343.1	407.6	64.5
Feedlot animals, × 10^3	419.9	480.3	60.4
Total animals slaughtered,[3] × 10^3	1,059	1,169	110
Total population,[4] × 10^3	3,266	3,651	385
Nutrition resources			
Total feed energy requirement,[5] MJ × 10^6	102,521	111,036	8,515
Feedstuffs, t × 10^3	26,807	29,637	2,830
Land, ha × 10^3	2,644	2,909	265
Water, L × 10^6	479,159	499,297	20,139
Fertilizers, N, P, and K, t	138,883	148,924	10,091
Fossil fuel energy, MJ × 10^6	4,093	4,406	313
Waste output			
Manure, t × 10^3	17,772	19,571	1,799
Nitrogen excretion, t	193,627	212,585	18,958
Phosphorus excretion, t	18,316	20,264	1,948
Greenhouse gas emissions			
Methane,[6] t	224,968	247,998	23,030
Nitrous oxide,[7] t	3,636	3,969	333
Carbon emissions,[8] t × 10^3	7,268	7,982	714

[1]Total may not sum due to rounding.

[2]Includes cows (lactating and dry), preweaning calves, heifers (<12 mo and >12 mo of age), and bulls (adolescent, yearling, and mature), prorated for the amount of time spent within each system.

[3]Includes cull animals. Total is not prorated but refers to total animals slaughtered.

[4]Includes all beef breed animals within the beef production system and calf-fed dairy animals prorated for the amount of time spent within each system, but excludes cull animals.

[5]Refers to nutrients required for maintenance (all animals), pregnancy (dry cows), and growth (all growing, replacement, and finishing animals).

[6]Includes CH_4 emissions from enteric fermentation and manure.

[7]Includes N_2O emissions from manure and inorganic fertilizer application.

[8]Includes CO_2 emissions from manufacture of cropping inputs, crop production and harvest, fuel combustion, electricity generation, and CO_2 equivalents from CH_4 and N_2O.

It is difficult to quantify the proportional contribution of poor water management (i.e., contamination that prevents its use as a potable source) to water scarcity. Nevertheless, public awareness of issues, such as the consequences of nutrient runoff into the Chesapeake Bay area, is growing. Animal agriculture is implicated in causing these issues, either directly through manure runoff or indirectly through the use of chemical fertilizers to grow feed crops. Aside from implementing good manure and nutrient management practices, a simple strategy to improve beef sustainability from a social, economic, and environmental standpoint would involve producing less manure, fewer nutrients (N and P) being excreted in waste, and using fewer chemical inputs (fertilizers, pesticides) per unit of beef. As is shown in Table 3, the reduction in productivity conferred by withdrawing GET from the beef production system would have the opposite effect, with increased manure production (10.1%), N excretion (9.8%), and P excretion (10.6%), compared with the CON system.

Anthropogenic carbon emissions have increased considerably over the past century as society has become more industrialized and the global population has increased. The global temperature is predicted to increase by 1.4 to 5.8°C by the year 2100, with acute, chronic, and evolutionary effects on crop and animal production (Root et al., 2002; UNFCCC, 2005; Parmesan, 2006; Challinor et al., 2007). Sector-specific strategies to reduce carbon emissions from food production are being instigated in many global regions, with considerable attention being focused on livestock production, due to its perceived contribution to global GHG emissions (Food and Agriculture Organization of the United Nations, 2006). Withdrawing GET from U.S. beef production would increase carbon emissions per 454×10^6 kg of beef by 714×10^3 t (9.8%; equivalent to 16.0 kg CO_2/kg HCW for the CON system vs. 17.58 kg CO_2/kg HCW for the NOT system) and fossil fuel use by 313×10^6 MJ (7.6%; Table 3), equivalent to $8{,}999 \times 10^3$ L of gasoline. This is in line with results of previous research by Capper (2011), who demonstrated that efficiency and productivity gains within the U.S. beef industry between 1977 and 2007 reduced the carbon emissions per kg of beef by 16%.

A comparison of calf-fed, yearling-fed, and grass-fed finishing systems also concurs with the overarching conclusion of the current study that productivity has a positive effect on environmental impact (Pelletier et al., 2010). Within this partial life cycle assessment (**LCA**), the calf-fed system (which exhibited fastest growth rates and fewest days on feed) used the fewest resources and had considerably less carbon emissions per unit of output compared with the yearling-fed system (intermediate in productivity and environmental impact) or grass-fed system (least productive, greatest environmental impact). Similar results were demonstrated by a previous study that evaluated the ecological impact of beef technology use, which demonstrated considerable decreases in land use and methane emissions, and increased habitat conservation in an intensive production system (Avery and Avery, 2007). Recent studies examining carbon emissions from beef production have acknowledged the role of productivity and concentrated on the potential for on-farm mitigation opportunities. Beauchemin et al. (2011) recommend a range of nutritional strategies, including polyunsaturated fatty acid supplementation and use of dried distillers grains, to reduce enteric methane emissions, in addition to improving livestock husbandry and longevity. Nonetheless, an LCA of beef production published by Beauchemin et al. (2010) demonstrated that improving productivity within the feedlot system had a relatively small impact on total GHG emissions from beef production, whereas the cow-calf operation accounted for ∼80% of total emissions. Within the current study, 74% of total GHG emissions were produced by the cow-calf operation; thus, there is significant potential to cut total emissions through mitigation strategies applied within this sector. However, a greater challenge to the beef industry is to continue to improve productivity within every sector, a challenge that is exacerbated by the need to maintain use of management practices and technologies that improve productivity, yet may have limited social acceptability.

It should be noted that the adoption rates of various technologies used in the CON system of the current model are specific to the current U.S. beef production system and that any increase or decrease in adoption rates would impact the magnitude of the results. The results are, therefore, both technology-specific and time-point specific, and should not be assumed to be representative of the impact of GET use in other systems. Nonetheless, the trends in differences between systems can be considered to be constant (e.g., withdrawal of GET use from the beef production system reduced growth rate, slaughter weight, and overall dressing percentage in the NOT population). Although not specifically accounted for within this analysis, it should also be remembered that the proportion of condemned tissues and digestive issues associated with whole-scale GET removal would also have significant environmental and economic implications due to reduced productivity in a NOT system. The effects of GET, specifically βAA, on tenderness and marbling in beef cattle vary between studies (Elam et al., 2009; Montgomery et al., 2009a,b; Parr et al., 2010), and, as the current study was designed to supply a constant amount of beef, it was assumed that beef quality and tenderness were unaffected by GET use. Nonetheless, potential effects of GET use on consumer perceptions of beef quality should not be discounted as reduced consumer demand for beef would have an intrinsically damaging effect on the economic viability of the U.S. beef industry. The limitations of the current study in regard to accounting for regional variations in feed production should also be acknowledged. The current study takes a national approach, using national cropping yields, rather than a regional approach. To definitively quantify the environmental impact of U.S. beef production, variation in feeding practices, crop and grass growth, climate, and other region-specific factors would necessitate the model to be run on a state-by-state basis to get a whole-scale analysis encompassing regional

Table 4. Impact of withdrawing growth-enhancing technologies (GET) from the U.S. beef production system on U.S. beef production and trade, and exports (1,000 t) from selected countries required to maintain total beef supply[1]

Region	2009	2010	2011	2012	2015	2018	2021	2022	2023
U.S. beef production									
Baseline	12,022	11,977	11,808	11,699	11,864	12,529	12,292	12,399	12,611
Change, %	0.1	1.2	–0.5	–1.6	–6.8	–12.3	–15.4	–16.1	–17.1
U.S. net imports									
Baseline	–700	–670	–653	–631	–515	–264	–551	–534	–476
Change, %	5.9	–4.9	15.3	26.7	107	409	258	287	352
Argentina net exports									
Baseline	376	425	434	448	492	573	757	817	872
Change, %	–1.9	–4.1	–1.0	0.4	6.7	12.3	11.1	10.9	10.9
Australia net exports									
Baseline	1,350	1,349	1,383	1,432	1,564	1,682	1,802	1,835	1,871
Change, %	–0.2	–0.5	–0.1	–0.2	0.6	2.7	4.5	5.0	5.4
Brazil net exports									
Baseline	1,920	2,048	2,195	2,270	2,453	2,461	2,830	2,907	2,982
Change, %	–1.3	–3.5	–1.3	0.1	7.8	17.2	21.1	22.5	24.8
Canada net exports									
Baseline	151	142	153	174	231	271	328	337	350
Change, %	–2.9	–6.9	–0.8	–0.7	6.1	20.9	30.3	33.9	36.3

[1]The results shown are derived from the appendix tables of Dumortier et al. (2010), substituting the 10% increase for the 8.2% increase in production costs derived from environmental and economic results within the current study. The model uses a midrange own price supply elasticity of 0.5 for pasture. To calculate these results, the model was used twice. The first time was a baseline where current trends are projected forward and the second time was a scenario where U.S. beef production costs were increased. The percent change numbers in this table represent the difference between the baseline and scenario.

variation. Although this is an acknowledged knowledge gap within the existing industry, it was considered by the authors to be beyond the scope of this study and provides an avenue for future research.

The environmental impacts of GET withdrawal have implications for both national cost and profitability of U.S. beef production, which also affects international price and competitiveness. Assuming that withdrawal of GET from U.S. beef production does not cause other countries to change their current regulations with respect to these products, an increase in the cost of producing beef in the United States would eventually stimulate decreased U.S. beef production, higher world beef prices, and increased beef production in countries, such as Canada, Australia, and Brazil, through competitive market forces.

Withdrawing GET from U.S. beef systems increased total production costs from \$3.14/kg beef to \$3.43/kg beef, a 9.1% increase. When adjusted for GET cost at \$0.0282/kg beef added to the aforementioned baseline costs described above, the total economic impact of withdrawing GET from the system is to increase costs by 8.2% (\$3.17/kg for CON vs. \$3.43/kg for NOT). Similar results were demonstrated as a result of technology use within U.S. beef production by Wileman et al. (2009). If everything else is held equal, a cost increase of this magnitude would reduce profits in the U.S. beef industry and eventually reduce national production, with significant effects of competition from pork and poultry, and also from beef production in other countries.

A model that estimates cross-commodity and cross-country impacts is required to calculate the full impact of GET withdrawal. The CARD Model (Center for Agricultural and Rural Development, Iowa State University, Ames) can be used to estimate the impact of any economic or policy change on supply, demand, price, trade, and carbon emissions. In this model, producers respond to changes in production costs and output prices, and consumers respond to changes in price levels for beef and other commodities, with key parameters estimated econometrically. The economic version of the CARD Model was published in Searchinger et al. (2008) and the carbon component by Dumortier et al. (2012).

A recent paper (Dumortier et al., 2010) used the CARD Model to examine the global economic and environmental implications of a 10% increase in the (farm level) production cost of U.S. beef production. This is of immediate relevance to the current study because the results can be adapted to examine the implications of GET withdrawal by simply substituting the 10% production cost used by Dumortier et al. (2010) by an 8.2% production cost increase (Table 4). The use of this earlier paper to calculate the economic and carbon impacts allows us to summarize key implications without the need for a lengthy description of model or scenario. Detailed specifi-

Table 5. Cumulative change (2009 to 2023) in carbon emissions from the baseline, resulting from withdrawing growth-enhancing technology use from U.S. beef production[1]

	Change in carbon emissions (10^6 t CO_2 equivalents)	
Country	Land use change	Agricultural production
Argentina	143	10
Australia	139	16
Brazil	2,157	123
Canada	283	36
China	–6	–1
European Union	–4	–1
Indonesia	190	11
India	–24	–6
Mexico	113	5
Philippines	32	2
Thailand	106	8
United States	–561	–255
Vietnam	464	55
Rest of world	103	9
Total	3,135	12

[1]The results shown are derived from the appendix tables of Dumortier et al. (2010), substituting the 10% increase for the 8.2% increase in production costs derived from environmental and economic results within the current study.

cations, data inputs, and parameters for the CARD Model can be found within Dumortier et al. (2010).

Table 4 shows the change in U.S. beef production and beef trade patterns for selected countries and years resulting from GET withdrawal in the United States. By 2023, U.S. beef production would have been reduced by 17.1% as U.S. beef production costs reduce the competitiveness compared with international competitors. To maintain world supply, other countries increase beef production. Canada shows the greatest increase in exports, with a 36.3% increase. Furthermore, Brazilian beef exports increase 24.8%, necessitating a significant increase in Brazilian beef production. This result should be noted as Brazilian beef production is pasture intensive and increases in beef production within this region have been associated with land conversion from native grasses and forests into pasture (Cederberg et al., 2009).

The increase in grass-fed beef production in Brazil seems to be somewhat counterintuitive, as the presence of foot-and-mouth disease (**FMD**) in Brazil means that it is prohibited from exporting beef to the United States and several other major beef-importing countries. Nonetheless, the European Union, Russia, and China purchase beef from Brazil; thus, FMD and non-FMD markets are linked in the CARD Model. A proportion of the extra Brazilian beef required to maintain global beef supply is based on new pasture land that is converted from scrubland or forest. The CARD Model measures the amount of carbon that had been stored in trees, their roots, and accounts for the carbon absorption that would have occurred over the remaining life of these trees had the land remained as forest or scrub. An increase in grass-fed beef production in Brazil, therefore, has a considerable potential impact on global GHG emissions from beef production, both in terms of land use change as discussed by Searchinger et al (2008) and because grass-fed beef has greater carbon emissions per kilogram than grain-fed beef (Capper, 2012; Subak, 1999). The global GHG results presented here are largely driven by land-use change due to an expansion of pasture area as grass-fed replaces grain-fed beef in international markets, although emissions from agricultural production (methane and nitrous oxide) are also included. The CARD Model assumes that whenever a beef industry expands, the amount of grain and pasture inputs increase proportionally. If the increase in beef production is achieved through better herd productivity, then this assumption will overstate carbon emissions. This assumption is particularly relevant because much of the change in carbon emissions is due to pasture expansion in Brazil. The key parameter here is the stocking rate elasticity. This is the percent change in pasture productivity for each 1% change in beef production. We performed a sensitivity analysis with respect to this stocking rate elasticity. If the value of this parameter is 0.1, implying that a 10% change in beef production increases worldwide pasture stocking rate density by 1%, then total carbon emissions fall by 33%. This sensitivity is high because our simulation assumed that pasture productivity on existing, as well as new pasture, increased by this amount.

Key global GHG results, expressed as the net cumulative increase in regional emissions between 2009 and 2023 when comparing the 2 scenarios (CON vs. NOT), are summarized in Table 5. Within the CARD Model, land use change is a major determinant of carbon emissions; thus, a modest increase in Brazilian beef production is responsible for a considerable increase in GHG. The United States would be predicted to reduce carbon emissions as a result of reduced beef production; however, this would not offset the dramatic increases in Brazilian and global emissions. The net increase in global emissions would be a cumulative $3{,}147 \times 10^6$ t of CO_2 equivalent from 2009 to 2023 inclusive. This is equivalent to 224.8×10^6 t annually. To put this into perspective, the FAO calculated that annual global emissions from livestock respiration in 2002 were $3{,}161 \times 10^6$ t annually and that total anthropogenic emissions were $38{,}461 \times 10^6$ t of CO_2 equivalent.

The withdrawal of GET from the U.S. beef production system would have significant consequences on environmental and economic sustainability, with increased resource use, waste output, carbon emissions, and production costs per kilogram of beef. Given that sustainability can only be achieved when environmental, economic, and social issues balance, arguments that focus solely on the environmental mitigation effects or economic benefit to the producer are unlikely to overcome consumer concerns relating to GET use. The challenge to the U.S. beef industry is to understand and overcome social concerns relating to GET use to ensure that a social license to operate is maintained. The oft-quoted definition of sustainability, "meeting the needs of the present without compromising the ability of future generations to meet their own needs," (United Nations World Commission on Environment and Development, 1987) has been widely accepted. It can be argued that by providing sufficient safe, affordable, nutritious beef to current and future generations, with concurrent reductions in environmental impact, the use of GET within beef production enhances sustainability, rather than simply maintaining it.

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